Thermoeconomic Analysis of a Solar Heat-Pump System

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Abstract: This paper introduces a solar energy heat-pump system and analyzes the thermoeconomics. The results show that the solar energy heat-pump system can be operated in different modes and used for room heating in winter and cooling in summer and/or heating a hot water supply. The results also show that the efficiency of the system's components and how the investment costs greatly affect the wide acceptability and use of the system. Solar energy is clean and renewable and having not to pay the solar energy costs, the solar energy heat-pump system is still attractive and will have a large market.

Key words: thermoeconomics analysis; solar heat-pump system; exergy; thermal collecting system; heat pump system

NOMENCLATURE

A_c	plate area
C	cost
E	energy
Ex	quantity of exergy
I_c	solar radiation projected on plate
P_{elec}	price of electricity
Q	heat
Q_u	utility energy from solar collector
T	temperature
U_{cl}	coefficient of total heat loss of collector
c	unit cost
c_p	specific heat of water at constant pressure
e	exergy per kilogram
h	enthalpy of refrigerant
m	mass flow
ΔE	exergy loss
α	plate absorptance
η_{ex}	exergy efficiency
τ	plate transmittance

subscripts

a	air
ac	accumulation
c	solar collector
cmp	compressor
con	condenser
csm	consumption
e	evaporator
eq	equipment
ge	generation
i	inlet
ld	room heating load
m	maintenance and management
o	outlet
p	plate
pc	product cost
r	refrigerant
sup	supply
s	solar
te	terminal equipment
v	expansion valve
w	hot water on user side

1. INTRODUCTION

Solar energy is clean and renewable, and there is no need to pay for energy cost. Many countries are paying much attention to using solar energy. Solar energy can be used in heating systems or a hot water supply (Kaygusuz 1995, Headley 1998, Song and Sun 2002). But, the solar radiation varies greatly with season, day, climate and region, it distributes unevenly and its quality is very low. When solar energy is used directly in heating systems, it can not achieve the appropriate temperature or gain enough heat to meet the requirements in high latitude regions. Several concepts (Hu et al. 2005, Ozgener and Hepbasli 2005, Wu et al. 2005) have been developed to use solar energy rationally in these regions. The solar energy heat-pump system discussed below is one of the most accepted concepts.

The solar energy heat-pump system provides hot water for heating systems or hot water supply by consuming a little high quality energy (e.g. electricity) to transfer solar energy into a higher quality thermal energy. The system can also provide

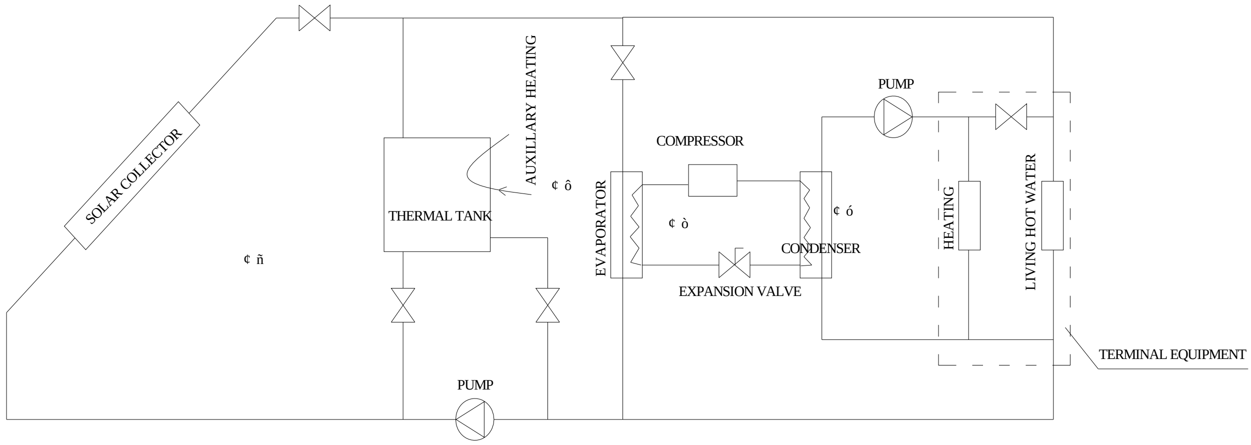

Fig. 1 Schematic diagram of the solar energy heat-pump system

chilled water and hot water simultaneously for users during the summer. Pollution to the environment is greatly reduced as well as the cost of energy. There have been many studies (Ozgener and Hepbasli 2005, Kuang et al. 2001, Wu et al. 2005) on the energy efficiency and the exergy efficiency related to the solar energy heat-pump system. But, the system is complex and has higher capital costs. This work focuses on the thermoeconomic analysis of solar energy heat-pump.

2. INTRDUCTION OF SOLAR ENERGY HEAT-PUMP SYSTEM

The solar energy heat-pump system consists of four subsystems: thermal collecting system (Ⅰ), heat-pump system (Ⅱ), user system (Ⅲ) and auxiliary heating system (Ⅳ), (see Fig. 1).

2.1 The Thermal Collecting System

The solar energy collected by the solar collector heats liquid (such as water) or air. Then heat is transmitted to the evaporator and vaporizes the refrigerant. As the specific heat of water is higher than that of air, water is normally adopted as the working medium. Other substances (e.g. ethylene-glycol solution) are used in cold climate to prevent freezing.

The solar collector is one of the key components in the system. The solar collectors used currently in the heating system may be classified as: plate solar collector, glass vacuum-tube solar collector, or heat pipe vacuum-tube solar collector, etc. The collecting efficiency and the attainable temperature increases as listed in the sequence above, but the cost is increased correspondingly. To keep the heating temperature above 60℃ is unnecessary, and helps to lower the cost of the system as well. The plate solar collector is the least cost and the best choice. Warm/hot water can be provided at 20~60℃ dependent on the surrounding air temperature.

Because solar radiation is not consistent the whole day, a thermal storage tank is needed in the system. The tank stores surplus heat collected during the day, then releases the heat when solar radiation is low. The heat-pump system (Ⅱ) can remain in steady operation.

2.2 The Heat-pump System

The heat-pump system consists of a compressor, an evaporator, a condenser and an expansion valve. Refrigerants R-407C or R-134a are usually used in the heat-pump system.

The evaporator and the condenser are both used as heat exchangers. Heat is transmitted from the low-temperature (T_L) heat source to the refrigerant in the evaporator. While in the condenser, heat is transmitted from the refrigerant to the high-temperature (T_P) heat source.

According to the second law of thermodynamics, the heat can not be transmitted from a low temperature source to a high temperature source without an external cause. A high quality energy source is needed (see Fig. 2), and consumed to drive the compressor. The compressor provides circulation to the system and keeps the evaporator and the condenser at a definite pressure.

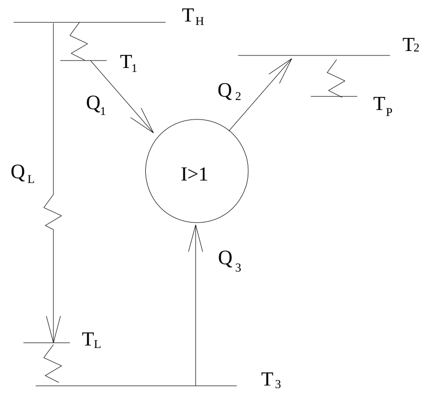

Fig. 2 Schematic diagram of a heat pump system

The function of the evaporator and the condenser can be interchanged by a four-way valve installed in the heat-pump system, then the system can become a chilling system providing chilled water to the users. Presently, most of the heat-pump systems are operating in this mode.

2.3 The User System

Heat coming from the heat-pump system can provide for heating loads or a hot water supply. The user system consists of terminal units, condenser and circulating pumps. The user system is connected with the heat-pump system through the heat exchanger or condenser. Usually the heat transfer medium in the system is water.

2.4 The Auxiliary Heating System

Solar radiation varies greatly with the season. In winter, the collecting temperature and the heat collected may not meet the needs. When solar radiation is too low to meet the needs, the shortages can be supplemented by the auxiliary heating system or apparatus, such as a geothermal heat-pump, a natural gas boiler or an electric heater. It is worth noting that auxiliary heating system should also be energy-saving and friendly to the environment, because the solar energy heat-pump system goals are energy savings and no pollution. At the same time, the auxiliary heating system control should be simple and reliable.

Generally, when storage capacity is capable of meeting the needs, the auxiliary heating system should not start up in order to save energy.

3. OPERATING MODES OF THE SOLAR HEAT-PUMP SYSTEM

The solar energy heat-pump system introduced above may operate in different modes as shown below:

3.1 The Thermal Collecting System Cooperating with the Heat-pump System (Mode 1)

The thermal collecting system (Ⅰ) cooperates with the heat-pump system (Ⅱ) to provide hot water to users in the winter.

In most cases, the solar energy heat-pump system runs in this mode in a cold climate. Energy collected by the solar collector heats water, then the heat in water is transmitted to the heat-pump system and pumped to the user system.

3.2 The Thermal Collecting System Operating in Winter (Mode 2)

The thermal collecting system (Ⅰ) is capable of providing hot water directly to the users in the winter.

This often occurs at the beginning or at the ending of the heating period when the heating load is low, and the collecting temperature and energy are high enough to meet the needs. Operating in this mode, the system will save more energy because there is no driving power needed. In a temperate climate, when the collecting temperature can attain to 50℃, the system may operate in this mode the whole winter.

3.3 The Heat-Pump System Provides Chilled Water for Air-Conditioning in Summer, While the Solar Collecting System Provides Hot Water Supply (Mode 3)

The heat-pump system (Ⅱ) provides chilled water for air-conditioning during the summer, while the solar collecting system (Ⅰ) provides the hot water supply.

The heat-pump system is changed into the chilling system. The function of the evaporator and the condenser can be interchanged through a four-way valve, then chilled water is provided to the users. Heat coming from the users warms water in the thermal tank, co-supplies hot water with the energy collected by the solar collector.

4. THERMOECONOMICS ANALYSIS OF THE SOLAR ENERGY HEAT-PUMP SYSTEM

4.1 Theoretics of Thermoeconomics

Thermoeconomics is a connecting discipline based on a thermodynamic analysis and an economic analysis. Generally exergy-based economic analysis methodologies are widely used and accepted. So thermoeconomic analysis is often referred to as exergoeconomic analysis (Wu et al. 2005). In this theory, the system or the component is evaluated based on the combination of quantity and quality of energy consumption and costs.

Three important balance equations are used in thermoeconomic analysis. Below are the thermodynamic balance equations in (1) and (2). The last equation (3) is the economic balance equation. They may be respectively written as follows (Wu et al. 2005):

Thermodynamic balance equations:

$$E_{\sup} - E_{pc} = E_{ac} \tag{1}$$

and

$$Ex_{\sup} - Ex_{pc} - Ex_{csm} = Ex_{ac} \tag{2}$$

Economic balance equation:

$$C_{\sup} + C_{ge} - C_{pc} = C_{ac} \tag{3}$$

Another model (i.e. exergoeconomic model) is introduced (see Fig. 3).

In this model, both exergy and costs involved are considered. Thus the exergoeconomic balance equation may be written as:

Product cost=Exergy input×Unit supply exergy cost+Equipment cost+Maintenance cost (4a)

or

Exergy output×Unit product exergy cost= Exergy input×Unit supply exergy cost+Equipment cost +Maintenance cost (4b)

Eqs. (4a) and (4b) can be expressed as

$$C_{pc} = Ex_{\sup} \cdot c_{\sup} + C_{eq} + C_m \tag{5a}$$

$$Ex_{pc} \cdot c_{pc} = Ex_{\sup} \cdot c_{\sup} + C_{eq} + C_m \tag{5b}$$

In Eqs. (5a) and (5b), the last two items can be merged into one item, i.e. the investment costs. In order to keep all the items in the same unit, the total investment costs in the system's life cycle are evenly divided and converted into the investment costs per year.

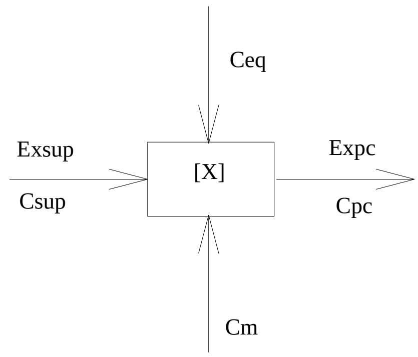

Fig. 3 The exergoeconomic model

In Fig. 3, [X] is the crucial parameter which influences all the product costs involved. It may be one or more than one variable or constant. For example, it may be the energy efficiency, the exergy efficiency, the social benefits and so on.

4.2 Thermoeconomics Analysis of the Solar Energy Heat-pump System

In winter, the solar energy heat-pump system operates mostly in Mode 1. as discussed above. The system is designed based on this mode and the following thermoeconomic analysis is based on this system concept. The system may be divided into three subsystems and each is analyzed respectively.

4.2.1 Exergoeconomic balance equations of thermal collecting system

This system consists of a solar collector, an evaporator and circulating pumps (see fig.4).

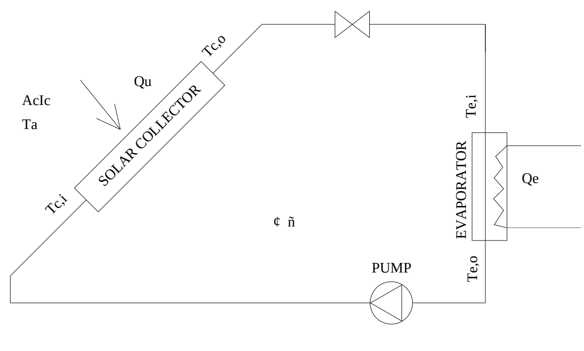

Fig. 4 Schematic diagram of the thermal collecting system

Work loss in the pumps and energy loss in the pipelines can be ignored because they are much less than those of the main components. The same applies in the other systems. Then the following equations are deduced corresponding to each component:

(1) The solar collector

Energy balance equation:

$$Q_u = A_c I_c (\tau\alpha) - A_c U_{cl} (T_p - T_a) \tag{6}$$

$$Q_u = m_c c_p (T_{c,o} - T_{c,i}) \tag{7}$$

Exergy balance equation:

$$A_c I_c \left(1 - \frac{T_a}{T_s}\right) - Q_{cl} \left(1 - \frac{T_a}{T_p}\right) = m_c (e_{c,o} - e_{c,i}) \tag{8}$$

Exergy loss:

$$\Delta E_c = A_c I_c - m_c (e_{c,o} - e_{c,i}) \tag{9}$$

Exergy efficiency:

$$\eta_{ex,c} = \frac{m_c (e_{c,o} - e_{c,i})}{A_c I_c (1 - \frac{T_a}{T_s})} \tag{10}$$

Exergoeconomic balance equation:

$$Ex_{\sup,ci} \cdot c_{\sup,ci} + Ex_{\sup,s} \cdot c_{\sup,s} + C_{eq,c} + C_{m,c}$$

$$= Ex_{pc,co} \cdot c_{pc,co} \tag{11}$$

As $c_{\sup,s} = 0$, then Eq. (11) can be expressed as

$$Ex_{\sup,ci} \cdot c_{\sup,ci} + C_{eq,c} + C_{m,c} = Ex_{pc,co} \cdot c_{pc,co} \tag{12}$$

(2) The evaporator

Energy balance equation:

$$Q_e = m_c c_p (T_{e,i} - T_{e,o}) = m_c c_p (T_{c,o} - T_{c,i}) = Q_u \tag{13}$$

$$Q_e = m_r (h_1 - h_4) \tag{14}$$

Eq. (14) expresses energy balance between the hot water and the refrigerant, it will be discussed in next part.

Exergy balance equation:

Exergy loss:

$$\Delta E_c = m_c (e_{e,i} - e_{e,o}) - m_r (e_1 - e_4) \tag{15}$$

Exergy efficiency:

$$\eta_{ex,e} = \frac{m_r (e_1 - e_4)}{m_c (e_{e,i} - e_{e,o})} \tag{16}$$

Exergoeconomic balance equation:

$$Ex_{\sup,ei} \cdot c_{\sup,ei} + Ex_{\sup,er4} \cdot c_{\sup,er4} + C_{eq,e} + C_{m,e}$$

$$= Ex_{pc,eo} \cdot c_{pc,eo} + Ex_{pc,er1} \cdot c_{pc,er1} \tag{17}$$

As

$$Ex_{\sup,ei} \cdot c_{\sup,ei} = Ex_{pc,co} \cdot c_{pc,co}$$

$$Ex_{pc,eo} \cdot c_{pc,eo} = Ex_{\sup,co} \cdot c_{\sup,co}$$

then, Eq. (17) can be expressed as

$$Ex_{\sup,er4} \cdot c_{\sup,er4} + C_{eq,c} + C_{m,c} + C_{eq,e} + C_{m,e}$$

$$= Ex_{pc,er1} \cdot c_{pc,er1} \tag{18}$$

4.2.2 Exergoeconomic balance equations of the heat-pump system

The heat-pump system consists of a compressor, an evaporator, a condenser and an expansion valve (see Fig. 5). It is related with the thermal collecting system and the user system through the evaporator and the condenser respectively.

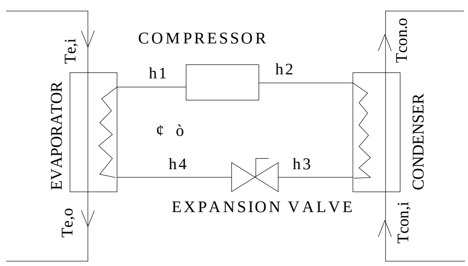

Fig. 5 Schematic diagram of the heat-pump system

The equations of each component are described as below:

(1) The evaporator

The equations of the evaporator have just been discussed above. They are written as Eqs. (13), (14), (15), (16) and (18).

(2) The compressor

Energy balance equation:

Theoretical power consumption:

$$W_{th} = m_r (h_2 - h_1) \tag{19}$$

Actual power consumption:

Considering the factors of the compressor's indicated efficiency (η_i) and friction efficiency (η_m), and motor's transmitting efficiency (η_p), actual power consumption can be written as

$$W_{cmp} = \frac{W_{th}}{\eta_i \eta_m \eta_p} \tag{20}$$

Exergy balance equation:

Exergy loss:

$$\Delta E_{cmp} = W_{cmp} - m_r (e_2 - e_1) \tag{21}$$

Exergy efficiency:

$$\eta_{ex,cmp} = \frac{m_r (e_2 - e_1)}{W_{cmp}} \tag{22}$$

Exergoeconomic balance equation:

$$Ex_{\sup,cmp} \cdot c_{\sup,cmp} + Ex_{\sup,cmpr1} \cdot c_{\sup,cmpr1} + C_{eq,cmp} + C_{mc} = Ex_{pc,cmpr2} \cdot c_{pc,cmpr2} \tag{23}$$

As

$$Ex_{\sup,cmpr1} \cdot c_{\sup,cmpr1} = Ex_{pc,er1} \cdot c_{pc,er1}$$

$$Ex_{\sup,cmp} = W_{cmp}, \quad C_{\sup,cmp} = P_{elec}$$

Eq. (23) then becomes

$$Ex_{pc,er1} \cdot c_{pc,er1} + W_{cmp} \cdot P_{elec} + C_{eq,cmp} + C_{m,cmp} = Ex_{pc,cmpr2} \cdot c_{pc,cmpr2} \tag{24}$$

(3) The condenser

Energy balance equation:

$$Q_{con} = m_r (h_2 - h_3) = m_w c_p (T_{w,o} - T_{w,i}) \tag{25}$$

Exergy balance equation:

Exergy loss:

$$\Delta E_{con} = m_r \left(e_2 - e_3\right) - m_w (e_{w,o} - e_{w,i}) \tag{26}$$

Exergy efficiency:

$$\eta_{ex,con} = \frac{m_w (e_{w,o} - e_{w,i})}{m_r (e_2 - e_3)} \tag{27}$$

Exergoeconomic balance equation:

$$Ex_{\sup,conr2} \cdot c_{\sup,conr2} + Ex_{\sup,coni} \cdot c_{\sup,coni} + C_{eq,con} + C_{m,con} = Ex_{pc,conr3} \cdot c_{pc,conr3} + Ex_{pc,cono} \cdot c_{pc,cono} \tag{28}$$

As

$$Ex_{\sup,conr2} \cdot c_{\sup,conr2} = Ex_{pc,cmpr2} \cdot c_{pc,cmpr2}$$

then Eq. (28) becomes

$$Ex_{pc,cmpr2} \cdot c_{pc,cmpr2} + Ex_{\sup,coni} \cdot c_{\sup,coni} + C_{eq,con} + C_{m,con} = Ex_{pc,conr3} \cdot c_{pc,conr3} + Ex_{pc,cono} \cdot c_{pc,cono} \tag{29}$$

(4) The Expansion Valve

Energy balance equation:

$$h_3 = h_4 \tag{30}$$

Exergy balance equation:

Exergy loss:

$$\Delta E_v = m_r (e_3 - e_4) \tag{31}$$

Exergoeconomic balance equation:

$$Ex_{\sup,vr3} \cdot c_{\sup,vr3} + C_{eq,v} + C_{m,v} = Ex_{pc,vr4} \cdot c_{pc,vr4} \tag{32}$$

As

$$Ex_{\sup,vr3} \cdot c_{\sup,vr3} = Ex_{pc,conr3} \cdot c_{pc,conr3}$$

$$Ex_{pc,vr4} \cdot c_{pc,vr4} = Ex_{\sup,er4} \cdot c_{\sup,er4}$$

the solution of Eqs. (18), (24), (29) and (32) can be written as

$$W_{cmp} \cdot P_{elec} + Ex_{\sup,coni} \cdot c_{\sup,coni} + (C_{eq,c} + C_{eq,e} + C_{eq,cmp} + C_{eq,v}) + (C_{m,c} + C_{m,e} + C_{m,cmp} + C_{m,con} + C_{m,v}) = Ex_{pc,cono} \cdot c_{pc,cono} \tag{33}$$

(5) The heat-pump system

Energy balance equation:

$$Q_e + W_{cmp} = Q_{con} \tag{34}$$

Exergy balance equation:

Exergy loss:

$$\Delta E_{hp} = \Delta E_e + \Delta E_{cmp} + \Delta E_{con} + \Delta E_v =$$

$$m_c(e_{e,i} - e_{e,o}) + W_{cmp} - m_w(e_{w,o} - e_{w,i}) \tag{35}$$

Exergy efficiency:

$$\eta_{ex,hp} = \frac{m_w(e_{w,o} - e_{w,i})}{m_c(e_{e,i} - e_{e,o}) + W_{cmp}} \tag{36}$$

Exergoeconomic balance equation:

The exergoeconomic balance equation of the system is just the same as Eq. (33)

$$W_{cmp} \cdot P_{elec} + Ex_{\sup,coni} \cdot c_{\sup,coni} + (C_{eq,c} + C_{eq,e} + C_{eq,cmp} + C_{eq,con} + C_{eq,v}) + (C_{m,c} + C_{m,e} + C_{m,cmp} + C_{m,con} + C_{m,v}) = Ex_{pc,cono} \cdot c_{pc,cono} \tag{33}$$

4.2.3 exergoeconomic balance equations of the user system

The user system is connected with the heat-pump system by the condenser. Heat transmits from the heat-pump system to the user system through the condenser. The user system consists of a condenser, terminal units and circulating pumps (see Fig. 6).

(1)The condenser

All the equations have been written in heat-pump system, (see Eqs. (25), (26) and (29)).

(2) The terminal units

Energy balance equation:

$$Q_{te} = m_w c_p (T_{w,o} - T_{w,i}) = Q_{con} \tag{37}$$

Exergy balance equation:

Exergy loss:

$$\Delta E_{te} = m_w \left(e_{w,o} - e_{w,i}\right) \tag{38}$$

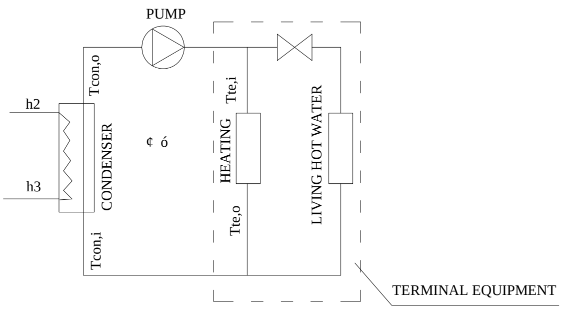

Fig. 6 Schematic diagram of the user system

Exergoeconomic balance equation:

$$Ex_{\sup,tei} \cdot c_{\sup,tei} + C_{eq,te} + C_{m,te} = Ex_{pc,teo} \cdot c_{pc,teo} + Ex_{pc,ld} \cdot c_{pc,ld} \tag{39}$$

As

$$Ex_{\sup,tei} \cdot c_{\sup,tei} = Ex_{pc,cono} \cdot c_{pc,cono}$$

$$Ex_{pc,teo} \cdot c_{pc,teo} = Ex_{\sup,coni} \cdot c_{\sup,coni}$$

Eq. (39) becomes

$$W_{cmp} \cdot P_{elec} + \sum C_{eq} + \sum C_m = Ex_{pc,ld} \cdot c_{pc,ld} \tag{40}$$

4.2.4 exergoeconomic balance equation of the solar energy heat-pump system

In fact, Eq. (40) is also the exergoeconomic balance equation of the solar energy heat-pump system. $\sum C_{eq}$ is the sum costs of the components including the solar collector, the heat-pump and the terminal units. $\sum C_m$ is the sum costs of management, maintenance and operation, which are distributed evenly to every year in the system's life cycle.

5. ANALYSIS

According to Eq. (40), the electricity consumed by the compressor, the price of electricity, the components costs, the costs of maintenance, management or operation are the factors influencing the system's thermoeconomics. But, the sum of solar energy consumed does not affect the thermoeconomics because of no paying for solar energy. So we can draw a conclusion that using solar energy can reduce the operating costs and yield good economic returns.

We can also know from Eq. (40) that if the components costs increase, the economic returns become poor. Though solar energy can be freely used, the collector area should not be infinitely large because the collector's cost is too high presently. So the collector area should not be designed to meet the heating loads at the most disadvantageous condition.

When divided by $Ex_{pc,ld}$ on both sides, Eq. (40) becomes

$$(W_{cmp} \cdot P_{elec} + \sum C_{eq} + \sum C_m) / Ex_{pc,ld} = c_{pc,ld} \quad (41)$$

$c_{pc,ld}$ may be used to evaluate the economics of the system. When keeping $Ex_{pc,ld}$ a constant, if $c_{pc,ld}$ is low, $W_{cmp} \cdot P_{elec} + \sum C_{eq} + \sum C_m$ is low, which shows the system has good economic efficiency.

It is worth noting that the energy efficiency and the exergy efficiency of the components also affects the thermoeconomics of the system, which can not be showed directly in the equations. It is included in the item *[X]* in the exergoeconomic model (see Fig. 3.). It is important to keep the components at a high energy efficiency and exergy efficiency. When the energy efficiency and the exergy efficiency are higher, $Ex_{pc,ld}$ gets higher, $c_{pc,ld}$ is correspondingly lower.

6. DISSCUSSIONS

The analysis above is based on operating Mode 1. In fact, the system should run in different modes when the surrounding air temperature changes. In winter, when the thermal collecting system can provide hot water below 50℃, Mode 1 is adopted. Otherwise, the thermal collecting system provides hot water directly to the room heating.

When the thermal collecting system provides hot water directly to the room heating, the item $W_{cmp} \cdot P_{elec}$ in Eq. (41) is omitted, and $c_{pc,ld}$ gets lower.

7. CONCLUSIONS

The system discussed in this work can operate economically in different modes dependent on the surrounding air temperature.

Using solar energy can reduce the operating costs and gain good economic benefits.

The work is intended to analyze the thermoeconomics of the solar energy heat-pump system and its influencing factors.

To keep the components at a high energy efficiency and exergy efficiency can also gain good economic benefits.

8. ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the YOUTH TEACHER FUND OF NORTH CHINA ELECTRIC POWER UNIVERSITY and the NATIONAL PRIORITY LABORATORY OF THE MINISTRY OF EDUCATION OF CHINA.

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